Monitoring the Fresh-Air Flow Rate for Energy-Efficient Bus Ventilation

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Abstract. City busses and coaches are typically ventilated with high fresh air rates without monitoring of air quality according to recommendations and requirements of associations of public transport companies. The air quality of cabin air regarding humidity and CO_2-concentration depends however on the number of passengers. Hence the air quality of the ambient air could be monitored and air conditioning units could be switched on re-circulation air, which is called here "*monitored fresh air rate*". Average occupancy of city busses is 30 %. This means the cabin will be ventilated with a surplus of about 70 % of the required fresh air. This causes a high energy consumption which could be saved. The aim of this work is the monitoring of the cabin air quality with the help of sensors and development of appropriate control algorithms that could reduce energy consumption without any impairment of safety, comfort, stress and health.

Keywords: Busses · Fresh air rate · Air quality · Cabin humidity · CO_2-concentration · Control algorithms

1 Current Situation

The air quality in busses influences passenger comfort and health conditions. Furthermore, air quality also affects safety aspects such as fogging of wind shield and increased driver's stress at uncomfortable conditions.

Therefore high air exchange rates are recommended or requested for cabin air by VDV (Association of German Transport Companies) [2] for city busses, with 15 m^3/h per passenger, and by GBK (Quality Association of Bus Comfort) [3], with a 75-times per hour air exchange for parked coaches for quality levels 3–5.

Based on these overall requirements current ventilation of busses is carried out independently of the number of passengers, assuming instead full occupancy. The number of transported passengers varies very widely in the course of the day, with average occupancy of 30 % in city busses. This means, in most times energy is wasted with heating and cooling fresh air that actually is not needed to desired temperatures.

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2 Motivation and Objectives

Increased requests of customers to reduce fuel consumption and also the European commission's communication COM(2014) 285 "Strategy for reducing Heavy-Duty Vehicles' fuel consumption and CO_2-emissions" [4] make it necessary to develop solutions for commercial vehicles with reduced fuel consumption and thus reduced CO_2-emissions.

Besides optimization of the primary power train, fuel consumption reduction of the secondary consumers is getting increasingly attractive. Here aggregates for heating and air conditioning of passenger compartments are the largest secondary consumers.

There are different known concepts to improve the cooling and heating performance. Reducing the fresh air rate in to the vehicle cabin depending on the number of passengers (and hence the air quality) is a possibility with a performance improvement high potential.

The actual thermal load by external and internal effects can be controlled also by re-circulating air, if the quality of cabin air is controlled simultaneously.

City busses are particular interesting for energy efficient ventilation because their occupancy widely varies between 0–100 % throughout the day, and with an average occupancy of about 30 % included rush hours. Besides different level of occupancy, door opening phases can are influencing cabin air conditions significantly. Moreover, external conditions can change very quickly due to mobility of the bus, and these can influence cabin air conditions. Energy efficiency of city busses is besides environmental aspects a specific requirement of public transport companies.

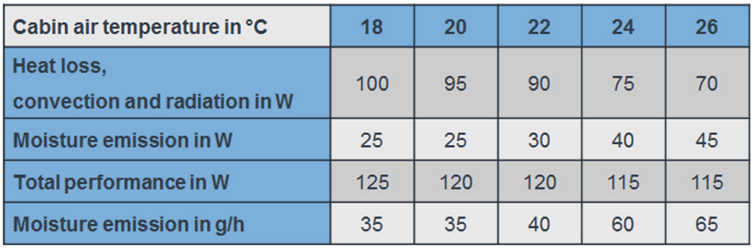
3 Monitoring Parameter and Control Algorithms

The most relevant monitoring parameters of air quality are the air humidity and the CO_2-concentration of the air. The concentration of harmful gases from ambient air, e.g. exhaust gases, hydrocarbons, etc. will be detected by external air quality sensors and the gases will be refrained from the vehicle cabin by filters or by flap switching to re-circulation air. The cabin humidity content and CO_2-concentration is hence directly influenced by number of passengers. The CO_2-concentration is also a good indicator for estimating bus occupancy, since passengers are generally the sole source of CO_2-emissions within the bus [14].

Every passenger breathes out a CO_2-volume flow of 12–20 l/h depending on the level of activity, and water vapor up to 65 g/h depending on the temperature [9, 13] (see Fig. 1). Additional humidity is added to the cabin by clothes, etc. This needs to be removed from the cabin or reconditioned in order to maintain the acceptable limits of comfort, health and safety and to meet legally required maximum limits.

With a concentration about 400 ppm CO_2 is a natural content of ambient air [14]. A rising CO_2-concentration increases the discontent of passengers. Even at an allowed CO_2-concentration about 2000 ppm the discontent increases to over 40 % [8] (see Fig. 2).

High CO_2-concentrations in vehicle cabins can cause health issues from indisposition up to critical state of health like sickness, headache and difficulties in



Cabin air temperature in °C	18	20	22	24	26
Heat loss, convection and radiation in W	100	95	90	75	70
Moisture emission in W	25	25	30	40	45
Total performance in W	125	120	120	115	115
Moisture emission in g/h	35	35	40	60	65

Fig. 1. Human heat and moisture exhalation at rest without solar radiation [9]

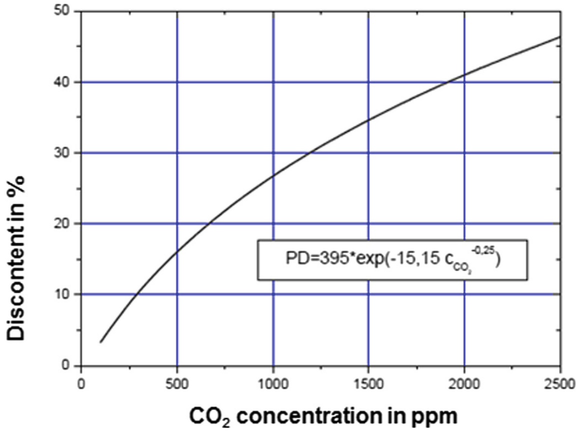


Fig. 2. Discontent depending on CO_2-concentration above ambient air concentration [8]

concentrating and – even up to unconsciousness. Therefor there have been CO_2-limits defined by Pettenkofer, DIN EN 13779 and ASHRAE 62-2001. According to Pettenkofer, the air quality in living spaces is excellent up to 1000 ppm. This limit cannot be transferred readily to vehicles due to specific differences. DIN EN 13779 requires a limit about 1500 ppm. According ASHRAE 62-2001, a CO_2-concentration of 2000 ppm is allowed at working places for 8 h [5–7, 12] (see Fig. 3).

Fogging on the wind shield due to high moisture content is safety relevant. In addition, humidity affects passenger comfort in the cabin. The higher the air temperature, the lower is the upper threshold for relative humidity with respect to comfort [2] (see Fig. 4).

Ambient conditions of a vehicle can change very quickly due to its mobility and hence the comfort level in the vehicle cabin, e.g. after entering a tunnel from a sunny ambient, or due to changing solar radiation because of shadowing or by changing of driving direction, which can change the temperatures of vehicle glasses, as well as the relative humidity in the cabin.

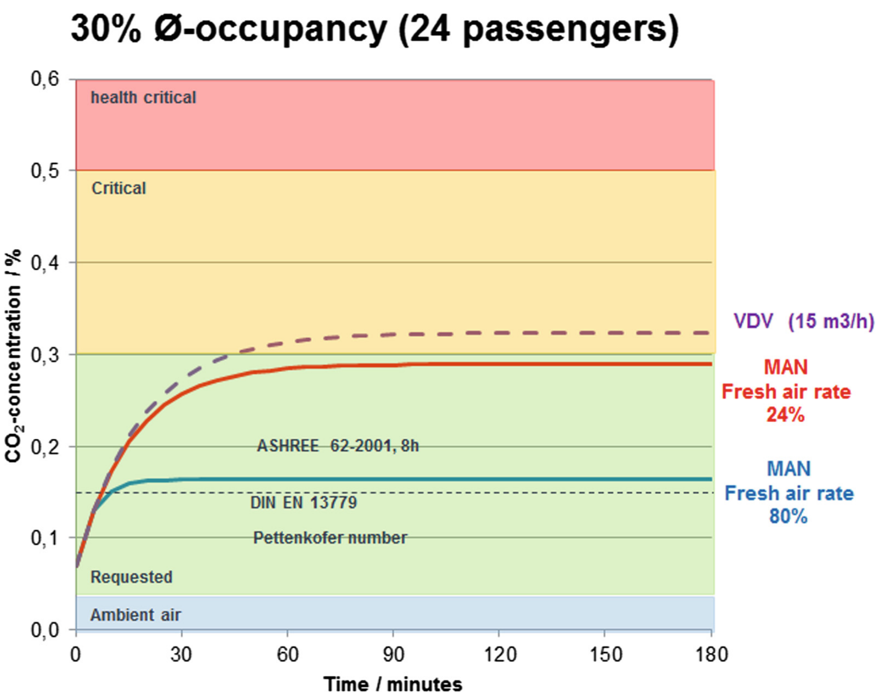


Fig. 3. CO_2-concentration depending on fresh air rate and compared to different standards [5–7]

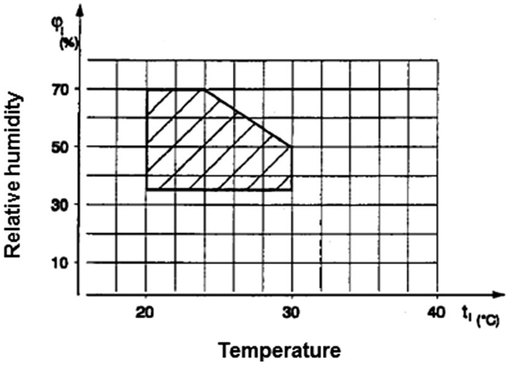
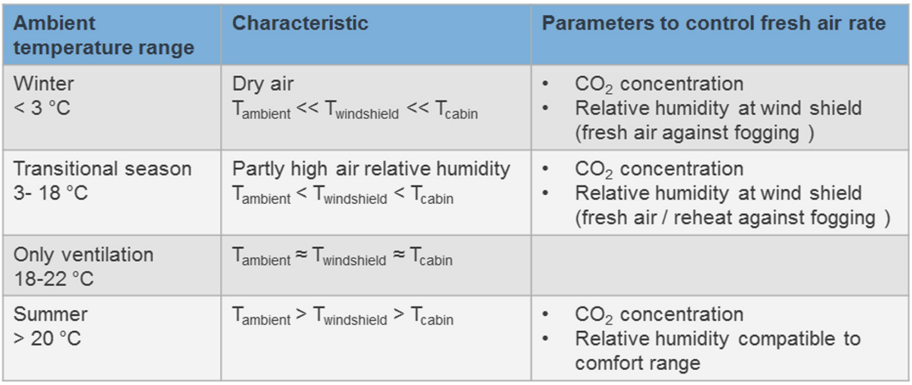


Fig. 4. Comfort zone depending on temperature and relative humidity [2]

4 Control Algorithms

While the CO_2-concentration in a bus cabin - according to the state of art - can only be influenced by controlling the amount of fresh air [11], the humidity of the cabin air can be effected by both fresh air ratio or reheat. Reheat is used in combination with low air volume flows and energy-intensive condensation of water vapor of the air. Instead, if pure fresh air is used for controlling air humidity, high air volume flows are required and condensation does not take place.

Therefore, control algorithms for energy-efficient monitoring of the fresh air rate are required, which account for conditions within and outside of the cabin. In this work ambient temperatures are split into four characteristic ranges (see Fig. 5). For these control algorithms differ considerably due to the differences in external conditions.



Ambient temperature range	Characteristic	Parameters to control fresh air rate
Winter < 3 °C	Dry air $T_{ambient} << T_{windshield} << T_{cabin}$	• CO_2 concentration • Relative humidity at wind shield (fresh air against fogging)
Transitional season 3- 18 °C	Partly high air relative humidity $T_{ambient} < T_{windshield} < T_{cabin}$	• CO_2 concentration • Relative humidity at wind shield (fresh air / reheat against fogging)
Only ventilation 18-22 °C	$T_{ambient} \approx T_{windshield} \approx T_{cabin}$	
Summer > 20 °C	$T_{ambient} > T_{windshield} > T_{cabin}$	• CO_2 concentration • Relative humidity compatible to comfort range

Fig. 5. Temperature ranges

In cold seasons with temperatures below 3 °C the humidity and CO_2-concentration is advantageously controlled by monitoring the fresh air rate, since reheat thermodynamically and due to icing risk of the evaporator is not attractive in this operating regime.

In transitional seasons (spring and autumn) at temperatures between 3 °C and 18 °C the air can contain high humidity, which could be insufficient dehumidifying the cabin air. In these cases and at sudden fogging of the wind shield, e.g. due to quick changes of conditions as a result of mobility, a reheat-operation could be needed inevitably. Additionally the CO_2-concentration of the cabin air needs to be considered. This temperature range is most interesting for energy optimization.

In the temperature range of 18–22 °C pure ventilation can be sufficient, if the internal and external thermal load can be balanced with this and the fresh air rate can be adjusted up to maximum. Therefore this range is not very relevant for an energetic optimization by controlling the fresh air rate.

In warm seasons over 20 °C the fresh air rate will be controlled depending on comfort considerations related to cabin humidity and CO_2-concentration, while fogging of the wind shield is not relevant.

In cooperation with Kempten University of Applied Sciences within a diploma thesis [1] (see Fig. 6), control algorithms for energy-efficient control of fresh air rates have been derived from process simulation depending on changing internal and external air conditions. By using of these simulations, fuel consumption was analyzed under realistic operating scenarios. The results show a high fuel consumption reduction potential by applying fresh air control strategies.

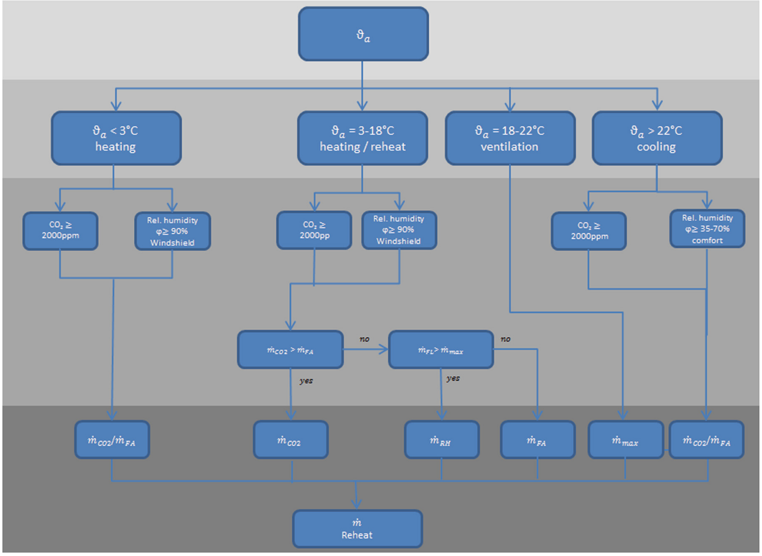


Fig. 6. Temperature ranges and control algorithms [1]

5 Comparison and Energy-Efficiency

Because of manifold factors which can impact ambient air conditions, especially in city busses, fuel consumption reduction by controlling fresh air rates can be reliable determined only by real measurements. For this purpose, MAN Truck & Bus AG has provided a customer bus with related sensors for field monitoring to determine the effect of different operating conditions like school holidays, weekends, rush hours, early and late drive services, different ambient conditions and other external influences like shadowing, tunnel driving, etc.

The city busses operate 20 h from 5:00 o'clock in the morning until 1:00 o'clock in the night with an annual mileage of about 60,000 km and an average speed of 16 km/h, whereby an average distance between two stops is 450 m and the average driving distance of passenger is about 4.5 km [10].

For this work representative data of three temperature ranges of weekdays were for further analysis. Presently MAN controls the fresh air rate only depending on ambient temperature, whereby the fresh air rate is reduced at extremely low and high temperatures in order to reach the desired temperature. Instead the new control strategy is controlling the fresh air rate by monitoring air qualities.

Fundamental the energy consumption will be determined by the internal load, solar radiation and the ambient temperature (thermal load and conditioning of fresh air), and by this the amount of fresh air.

The first case (see Fig. 7) investigates operation of a city bus during warm seasons (summer) within temperature ranges between 25 °C and 33 °C. During the day the temperatures increases up to 33 °C, while the ambient relative humidity changes little. Between 14:00–18:00 o'clock at high ambient temperatures the current control unit reduces the fresh air rate to reach the desired temperature of the cabin. Nevertheless the energy consumption is high due to high ambient temperatures. Both the current and new (monitored) control strategies have most similar fuel consumption in phases of high occupancies (about 8:00 o'clock and 18:00 o'clock). On the typical summer day shown, the potential of fuel consumption reduction is on average about 0.68 l/h which is comparably high, whereby the COP-values of the air conditioning unit are in average about 2.5.

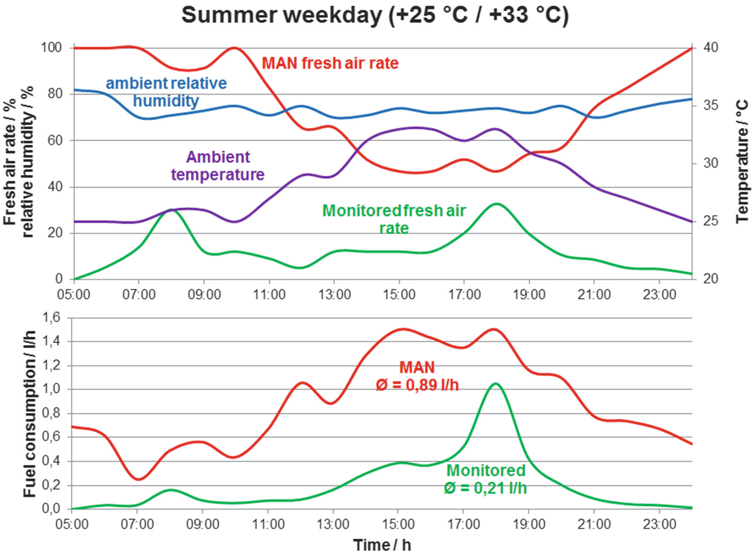


Fig. 7. Summer case

The second case (see Fig. 8) analyses operation during transitional season (spring and autumn) with a temperature range between 9 °C and 19 °C. The current control unit does not reduce the fresh air rate due to moderate temperatures. Nevertheless the fuel consumption is comparatively low, but with a high potential for fuel consumption reduction of on average 0.35 l/h, which is proportionally high due to a low COP of about 0.8 of the auxiliary heater.

The third and last case (see Fig. 9) represents a cold season (winter) with a temperature range between −14 °C and −6 °C with relative harsh ambient conditions. The current control unit de-throttles the fresh air rate with increased ambient temperatures. In early hours the controlled (monitored) fuel consumption gets close to those of the current control unit due to high occupancy of the city bus and high throttling of fresh air rates by the current control unit. At such a winter day the potential for fuel consumption reduction is on average 1.09 l/h, which is highest due to a low COP of auxiliary heater of 0.8 and due to big temperature differences between ambient and cabin temperatures.

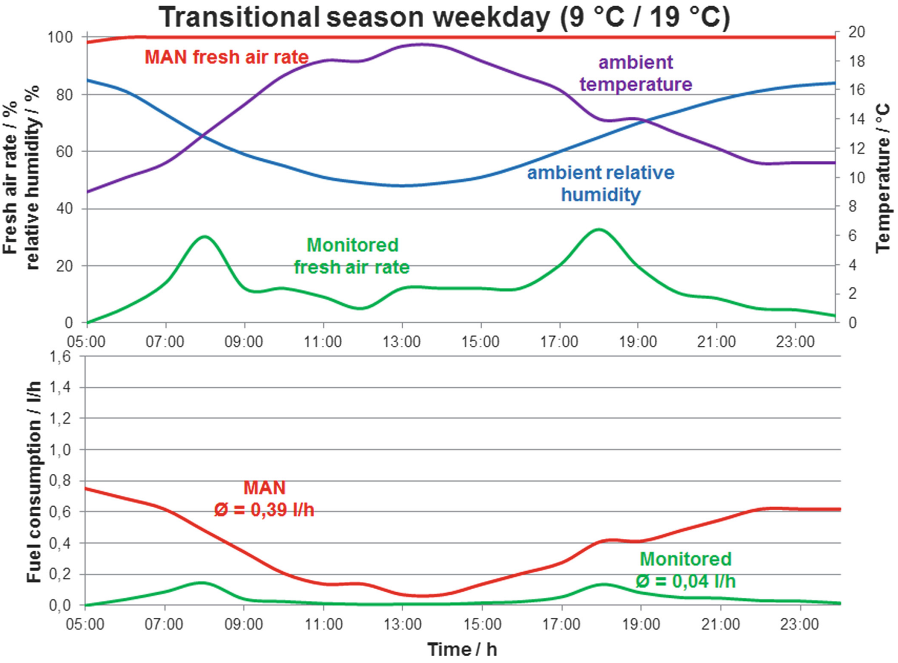


Fig. 8. Transitional season case

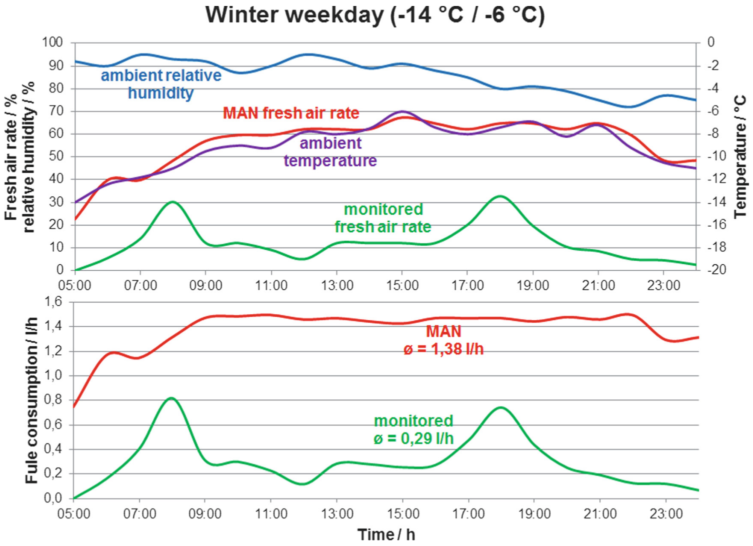


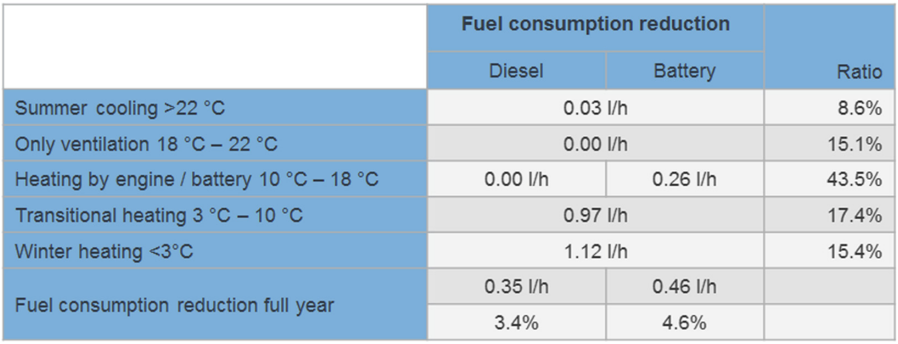
Fig. 9. Winter case

6 Annual Consideration

For estimating the potential for fuel consumption reduction different vehicles types need to be considered: diesel, hybrid and battery. The mixed type hybrid is however not considered in this investigation.

The most significant difference of potentials between of diesel and battery busses is in the temperature range of 10–18 °C, because heat demand is satisfied by engine heat for the diesel busses, while the battery busses need extra energy of their batteries.

The highest potential of fuel consumption reduction is at temperatures below18 °C: In winter below 3 °C due to big temperature differences of 17 K or more between ambient and cabin temperatures, and during transitional season of 3–18 °C due to the high occurrence of these temperatures with 60.9 % (see Fig. 10). The effect is increased by the low COP of the auxiliary heater of 0.8.



	Fuel consumption reduction		
	Diesel	Battery	Ratio
Summer cooling >22 °C	0.03 l/h		8.6%
Only ventilation 18 °C – 22 °C	0.00 l/h		15.1%
Heating by engine / battery 10 °C – 18 °C	0.00 l/h	0.26 l/h	43.5%
Transitional heating 3 °C – 10 °C	0.97 l/h		17.4%
Winter heating <3°C	1.12 l/h		15.4%
Fuel consumption reduction full year	0.35 l/h	0.46 l/h	
	3.4%	4.6%	

Fig. 10. Fuel consumption reduction

The results show the potential for fuel consumption reduction of about 3.4 % for diesel-city busses and of 4.6 % for battery-city busses.

This could be translated into a reduction of the annual fuel consumption of 750–1000 l depending on the bus type.

7 Summary and Outlook

The results show the high potential for fuel consumption reduction by controlling the fresh air rate, especially in city busses with an average occupancy about of 30 %.

The reduction of energy consumption in seasons with heating demand is highly relevant especially for electrified vehicles (battery-city busses) because of the impact on driving range and battery capacity.

If a heat pump is used for heating, the potential for fuel consumption below 18 °C is reduced correspondingly.

The position of the CO_2-sensor is important for determining the correct CO_2-concentration and hence the energy reduction potential, which can be relevant for future further investigations. There are spots within the bus with low air exchange und correspondingly high air aging. A CO_2-sensor placed in the recirculation air measures average CO_2-concentrations risking that not allowed high CO_2-concentrations in bus areas with high air aging are insufficiently detected.

These potentials for fuel consumption reduction could be further improved by individual or zonal air conditioning with corresponded sensors.

The monitoring and controlling of fresh air rates is also compatible with the latest recommendation of VDV, which is valid from 2017. Furthermore it is able to fulfill the expected directions of the European Commission with respect to future regarding CO_2-emission.

References

1. Gökoglu, M.: Diplomarbeit: Untersuchung zum Verbrauchseffekt des Frischluftanteils bei der Busbelüftung, Unveröffentlicht, June 2016
2. VDV-Schrift 236: Klimatisierung von Linienbussen der Zulassungsklassen I und II, für konventionell angetriebene Diesel- und Gasbusse sowie für Hybrid-, Brennstoffzellen- und Elektrobusse. VDV-Verlag, Köln, 6 Juni 2015
3. Gütesicherung RAL-GZ 791: Buskomfort. Beuth-Verlag GmbH, Berlin, May 2007
4. COM(2014) 285: Strategy for reducing Heavy-Duty Vehicles‘ fuel consumption and CO_2-emissions
5. ASHRAE Standard 62-2001: Indoor Air Quality (2002)
6. DIN EN 13779: Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. Beuth Verlag GmbH, Berlin, September 2007
7. Pettenkofer: Besprechung Allgemeiner auf die Ventilation bezüglicher Fragen. Über den Luftwechsel in Wohngebäuden. J.G. Cottaísche Buchhandlung, München (1858)
8. Fritzner, K., Finke, U.: Lüftungsregeln für freie Lüftung, Bundesanstalt für Arbeitsschutz und Medizintechnik (2012)
9. VDI 2078: Berechnung der thermischen Lasten und Raumtemperaturen. Beuth Verlag GmbH, Berlin, 2015
10. Leuthardt, H.: Die Wirtschaftlichkeit von Gelenkbussen und Buszügen, Der Nahverkehr, May 2010
11. Dougan, D.S., Damiano, L.: CO_2-based demand control ventilation. ASHREA J., October 2004
12. SIEMENS: Demand-controlled ventilation, control strategy and application for energy-efficient operation (2010)
13. Müller, R.: Atmung, Stoffwechsel und Blutkreislauf, Universität München
14. Umweltbundesamt: Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft. Springer Medizin Verlag (2008)